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90-Ampere-Hour Nickel-Hydrogen Dependent Pressure Vessel (DPV) Low Earth Orbit (LEO) Life Test Evaluation

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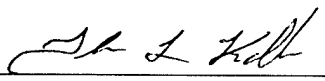

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14. ABSTRACT

Three 90-Ah dependent pressure vessel (DPV) battery packs are being LEO life tested at Crane. As of 9/10/01, the 40% DOD pack has completed 4,863 total cycles, and the 60% DOD pack has completed 2,885 total cycles. The third pack, formerly tested at 71% DOD but currently run at 60% DOD, had 2,067 total cycles as of 9/24/01. The philosophy of these tests is to minimize charging to maximize life, so all the packs started with low charge-discharge (C/D) ratios. As a result, the charge conditions of the packs, especially the two 60% DOD packs, have been changed to find the appropriate operating points for these cells and packs.

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1. Introduction

The dependent pressure vessel (DPV) is a new nickel-hydrogen cell design, where structural integrity under operation is provided at the battery level rather than at the cell level. Each DPV cell is shaped like a canteen, and the flat sides need to be restrained. Battery design is similar to that of nickel-cadmium batteries, with a stack of cells supported by connected end plates. The DPV design should have less volume than the traditional individual pressure vessel design (IPV), while maintaining advantages of having only one cell stack per pressure vessel. Fifteen 90-Ah DPV cells that were manufactured by Eagle-Picher Industries are currently being tested at the Naval Surface Warfare Center (NSWC) Crane Division. The cells went through a characterization test to establish beginning-of-life characteristics. One result of note from the characterization test is that strain gauges could be used to monitor internal cell pressure, but calibration of each strain gauge after pack assembly was required. Calibration factors for cells that were individually restrained cells were different from those in a five-cell pack. The cells were placed in three five-cell packs to determine LEO life performance at –5°C as a function of depth-of-discharge (DOD).

2. Pack E007D

Pack E007D commenced LEO life testing on 10/27/00 with a representative life cycle consisting of a 60-min charge and a 30-min discharge. The data presented cover the period through 9/10/01, when the cells had undergone 4,863 total cycles. The cells are charged at the high-rate current of 45 A until the average cell charge voltage limit, initially set at 1.53 V, is reached, followed by a taper charge for the balance of the charge period. The cells are then discharged at 72 A, resulting in a 40% DOD. This initial voltage limit resulted in an approximate percent return of 101%. Figure 1 represents the average cell end-of-charge (EOC) and end-of-discharge (EOD) voltages, as well as the C/D ratio. To increase the average EOD voltages, which were decreasing, the average cell charge voltage limit was incrementally increased from its value of 1.53 V to its present value of 1.55 V at cycle 384. This resulted in an increase in the state-of-charge of the cells and a current percent recharge of about 103%.

The individual cell discharge voltages are shown in Figure 2. The cell discharge voltage cutoff is set at 1.0 V. Figure 3 gives the individual cell charge voltages. Both Figures 2 and 3 indicate that the cells are fairly evenly matched and have a similar state-of-charge. With an increasing number of cycles, however, there is a trend towards a slight increase in cell EOD voltage divergence.

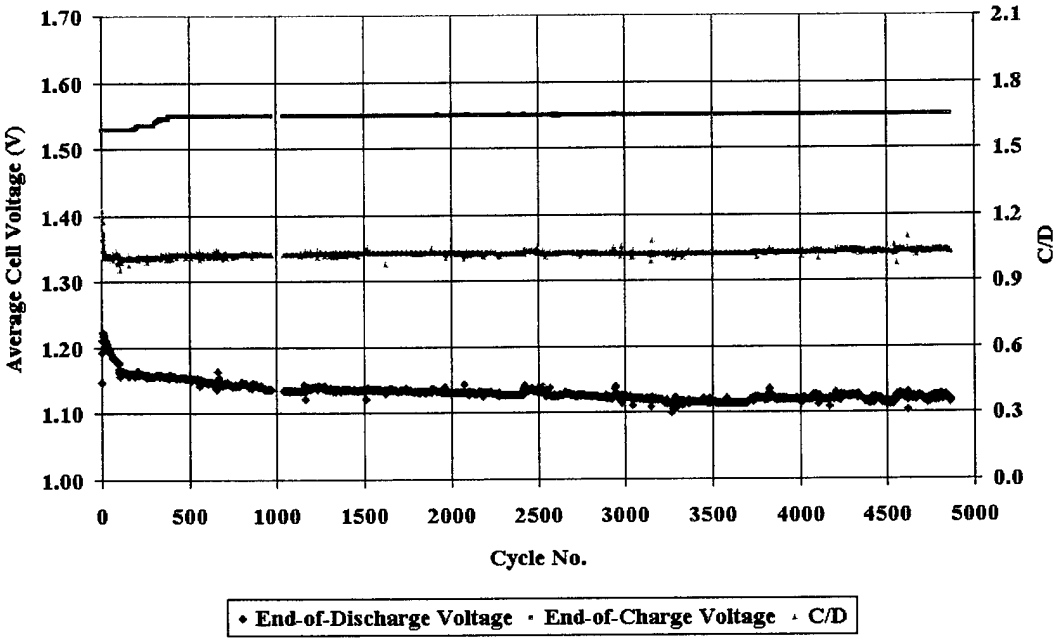

Figure 1. Pack parameters vs. cycle for E007D.

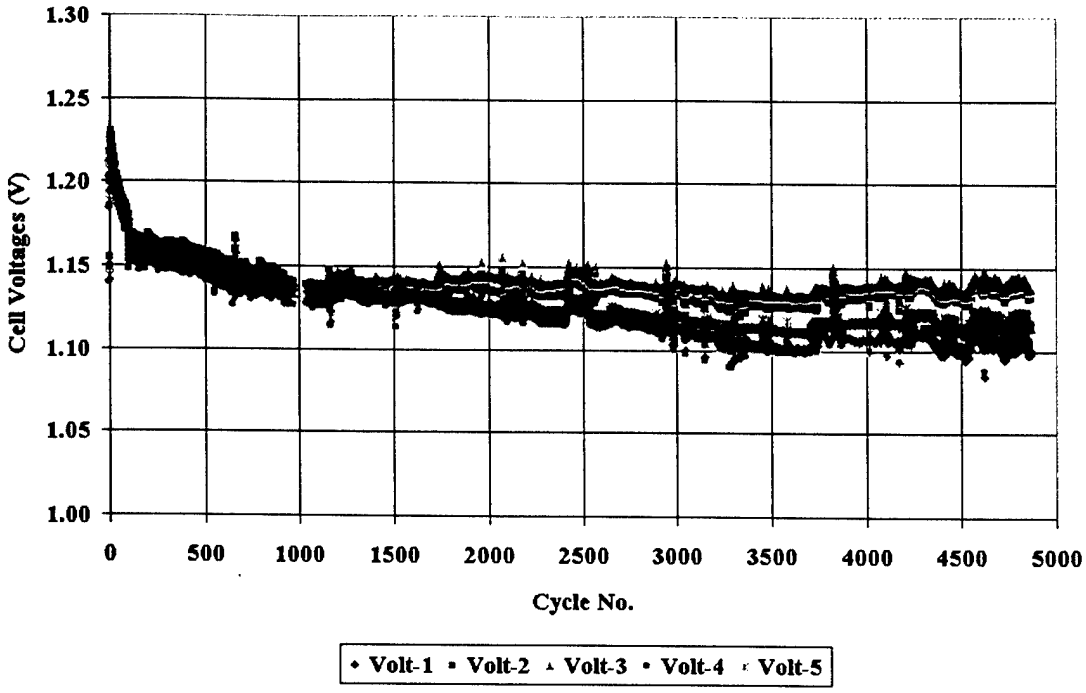

Figure 2. Cell EOD voltages vs. cycle for E007D.

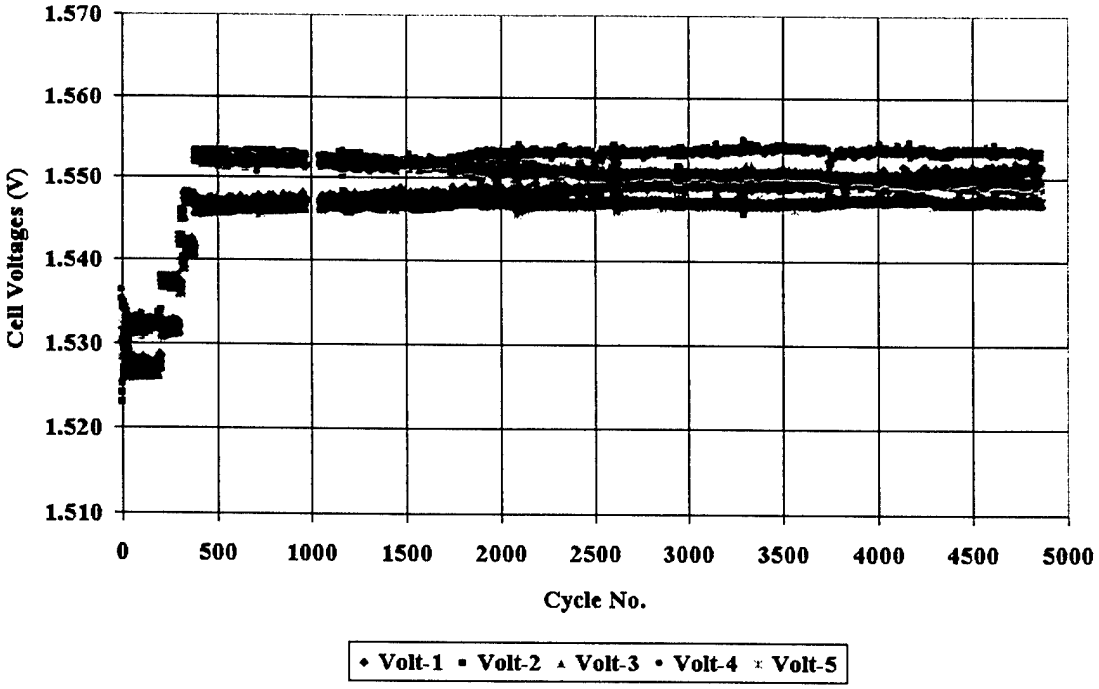

Figure 3. Cell EOC voltages vs. cycle for E007D.

3. Pack E008D

Since 1/8/01, pack E008D has been life tested at a DOD of 60%, with a typical LEO life cycle consisting of a 60-min charge and a 30-min discharge. As of 9/10/01, 2,885 total cycles have been completed. The cells are charged at a high-rate current of 68 A until the average cell charge voltage limit is reached. A taper charge for the balance of the charge and a discharge at 108 A follows. The initial average cell charge voltage limit of 1.56 V was incrementally increased to 1.585 V at cycle 680, then increased to its present value of 1.62 V during cycle 2,482. The percent return increased from about 101% at the start of life testing to its present value of 111% at cycle 2,885. This was done in an attempt to increase the state-of-charge of the cells; the walk-down in EOD voltages, especially those of cell 5, precluded the completion of a full discharge in some instances. This had occurred despite the fact that the cell discharge voltage cutoff was reduced from 1.00 V to 0.9 V. The individual cell discharge voltage profile is shown in Figure 4; an increase in cycling has resulted in an appreciable spread in EOD voltages. Figure 5 presents the individual cell charge voltages, where there is also an increase in spread with the EOC voltages, though cell 1 has been out-of-family from the beginning of cycling.

An internal impedance test, performed at approximately the six-month interval in accordance with the initial test plan, indicated that the cell with the highest impedance was cell 5. After cycle 2,480, a series of various tests, which included reconditioning, 72-h open-circuit stand, and 10°C capacity, were conducted to determine whether any internal shorts existed, as well as to ascertain the voltage characteristics and the capacity of the cells. The final 10°C capacity test was run at the end of these tests. The 10°C capacity test consisted of a charge at C/10 (9 A) for 16 h, followed by a discharge at

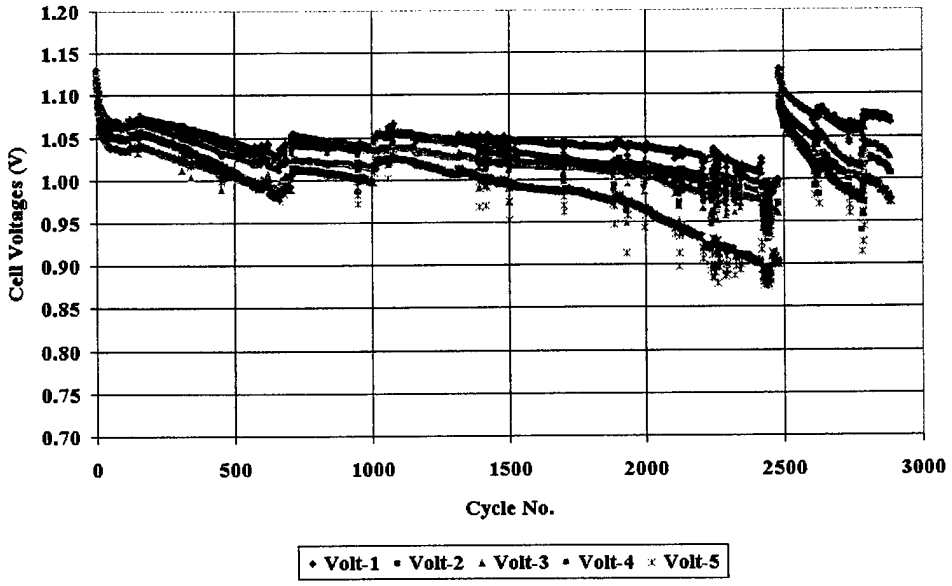

Figure 4. Cell EOD voltages vs. cycle for E008D.

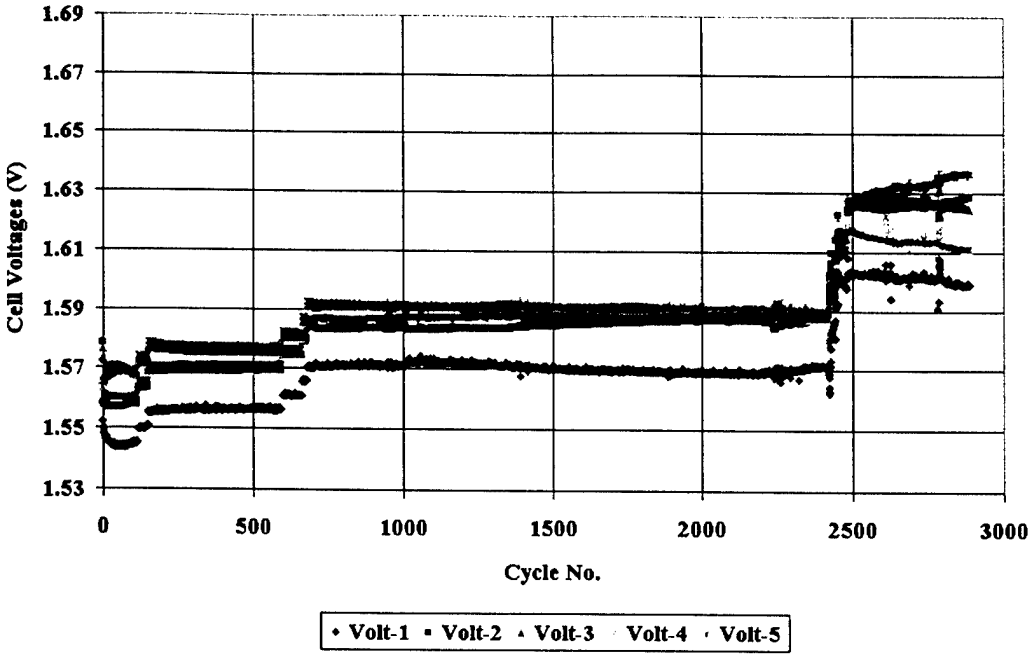

Figure 5. Cell EOC voltages vs. cycle for E008D.

C/2 (45 A) to 0.5 V for each cell. The capacity, measured to 1.0 V, ranged from 92.88 to 105.26 Ah. Cell 3 had the lowest capacity. The discharge portion of this test is illustrated in Figure 6. No anomalous performance had been observed in any of the testing, so it was thought that the cells were not being adequately charged during the LEO life testing. The average cell charge voltage limit was, therefore, increased to its present value of 1.62 V. Since the increase in the charge voltage limit, no cells have reached the discharge voltage cutoff of 0.9 V, although they appear to be walking down.

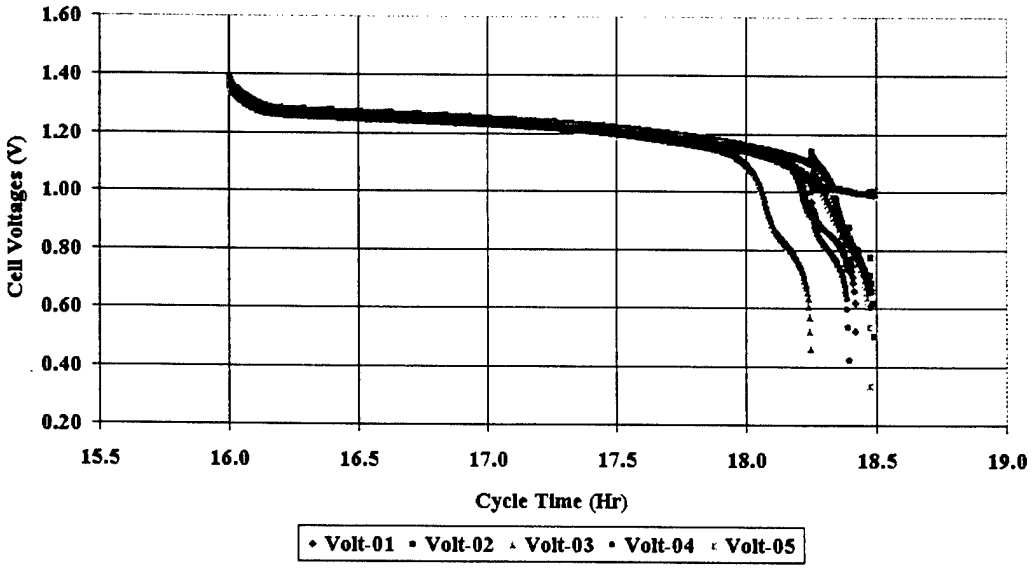

Figure 6. E008D 10°C capacity test.

4. Pack E009D

Pack E009D, which has been undergoing LEO life testing since 12/11/00, has completed 2,067 total cycles as of 9/24/01. For the first 1,537 cycles, the test was run at a DOD of 71%, where the typical life cycle consisted of a 74-min charge and a 36-min discharge. Once the average cell charge voltage limit, originally set at 1.55 V, was reached at the high-rate charge current of 68 A, the charge was then tapered. The subsequent discharge was at 106.5 A, with a cell discharge voltage cutoff of 1.0 V. This resulted in an approximate percent return of 101% and a DOD of 71%. Because the pack was having difficulty completing its full discharge, the average cell charge voltage limit was increased gradually to its final value of 1.595 V at cycle 731. The testing at 71% DOD was stopped after 1,537 cycles, when the low voltage of cell 4 was consistently dropping the pack out, prior to its completing a full discharge. The percent return had increased to a value of about 137% by the time the test was stopped.

After reconditioning, pack E009D was LEO life cycled at a reduced DOD of 60%, commencing with cycle 1,540. The only test parameters that were changed for the new DOD test were the discharge current at 90 A and the average cell charge voltage limit, which was set initially at 1.57 V. The resulting percent recharge was about 106%. The pack was again reconditioned just prior to cycles 1,603 and 1,643 in an attempt to increase the EOD voltages. The average cell charge voltage limit was increased from its initial value of 1.57 V to 1.575 V at cycle 1,660, to 1.59 V at cycle 1,775, and to its present value of 1.61 V at cycle 1,970. The cell discharge voltage cutoff was eventually reduced from 1.0 V down to 0.8 V in an attempt to complete a full discharge. Figure 7 illustrates the individual cell EOD voltages, while Figure 8 depicts the cell EOC voltages.

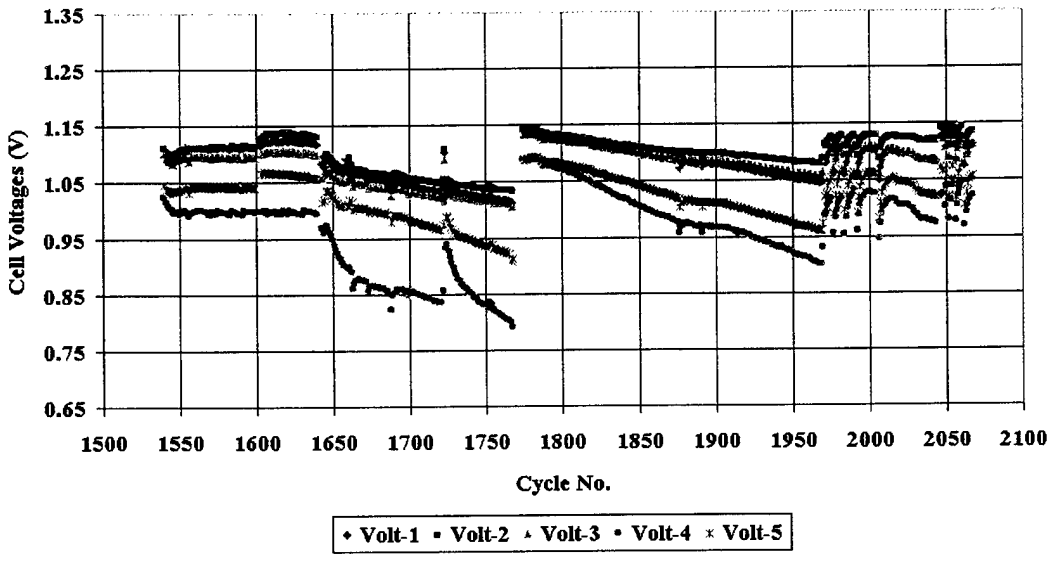

Figure 7. Cell EOD voltages vs. cycle at 60% DOD for E009D.

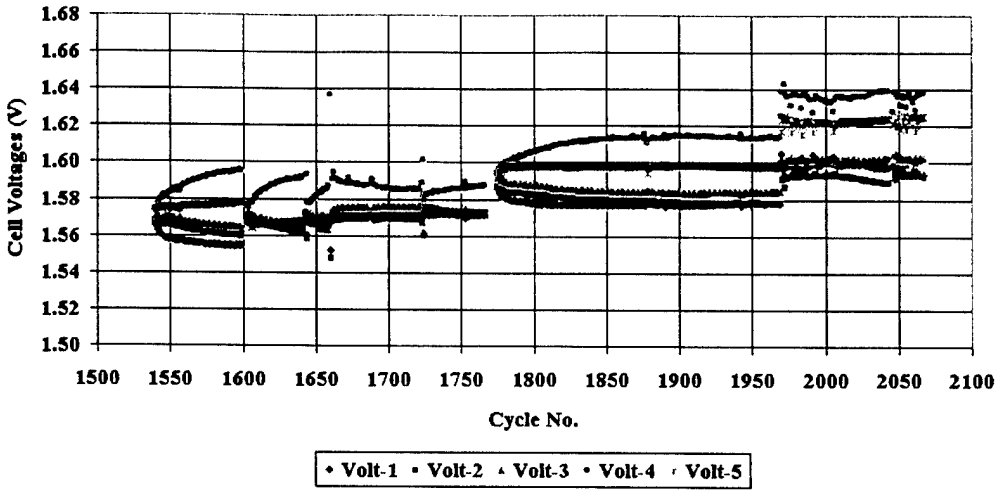

Figure 8. Cell EOC voltages vs. cycle for the 60% DOD test for E009D.

Cells 4 and 5, respectively, generally exhibit the lowest voltages during discharge and the highest voltages during charge (this occurs to a lesser extent with cell 5 during its charge). In addition, an internal impedance test, performed at approximately the six-month interval, indicated that the impedance was greatest within cell 4, followed by cell 5. All of this seems to indicate that the two weakest cells may be drying out.

With the same reasoning that was used for pack E008D, a series of various tests, which included reconditioning, 72-h open-circuit stand and 10°C capacity, were conducted. These tests were run after cycle 1,768. The final 10°C capacity, measured to 1.0 V, ranged from 105.62 to 112.33 Ah. Cells 1 and 2 had the lowest capacities. No anomalous behavior was observed in any of the testing, so the pack was placed back on life test. The average cell charge voltage limit was, therefore, increased to 1.59 V because it was believed that the state-of-charge should be increased. Walk-down of the voltages, particularly those of cell 4, resulted in the average cell charge voltage limit being further increased to its present value of 1.61 V. As of cycle 2,043, the percent return had increased to 125%. Roughly midway through the charge of cycle 2,044, cell 4 reached the voltage cutoff of 1.67 V. (These midpoint charge voltages are not plotted.) This resulted in shutting the test down during cycle 2,044. Consultations with Eagle-Picher indicated that all three packs were manufactured without a wall wick. It was speculated that if the electrolyte was settling in the bottom of the cell, instead of being reabsorbed by the plates, that cell dry-out could occur. This might help to explain the problems believed to be associated with the higher resistance of cells 4 and 5, as indicated in their voltage profiles. Subsequent to cycle 2,044, pack E009D was discharged at C/2 until the first cell reached 1.0 V, then the pack was rotated 180° so as to allow any electrolyte that may be at the bottom of the case to flow over the plates. The pack was then fully charged at C/10 for 16 h, prior to the restart of LEO life cycling in the newly rotated pack position, which commenced with cycle 2,046. The DOD was kept at 60%, as was the average cell charge voltage limit of 1.61 V. As compared to the EOD voltages of cycle 2,043, recorded just prior to the rotation of the pack, those seen in cycle 2,067 have slightly increased. The range of increase is from 16 mV to 47 mV. Cells 4 and 5, which had the lowest EOD voltages, saw the largest increases of 47 mV and 38 mV, respectively. The EOC voltages have remained essentially the same, within 4 mV, from comparisons between cycles 2,043 and 2,067. Therefore, it remains to be seen as to whether a significant improvement in the cell voltages will occur as a result of rotating the pack. The percent recharge at cycle 2,067 was about 122%.

5. Summary

All three packs started cycling at low charge-discharge ratios to minimize degradation from overcharge. Pack E007D, which is being tested at the lowest DOD of 40%, has performed well and completed over 4,800 total cycles. The operating conditions of the other two packs, each currently at 60% DOD, have been gradually modified to find the appropriate conditions for these cells. Pack E008D is being tested at 60% DOD and has completed over 2,800 total cycles. Pack E009D has completed over 2,000 total cycles and was originally tested at 71% DOD for 1,537 of those cycles. Low discharge voltage resulted in the test being modified to run at 60% DOD. The cycling continued until high charge voltage halted the test during cycle 2,044. The pack was then rotated 180° to allow any electrolyte that may be at the bottom of the case to flow over the plates since cell dry-out could be occurring. This is especially seen with the two cells that show the signature for high internal impedance. Life cycling was then resumed. Testing to determine the cause of the suspected high internal impedance is in progress.

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